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Impact of Hydrotechnical Structures on Forming the Tombolo Oceanographic Phenomenon in Kołobrzeg and Sopot

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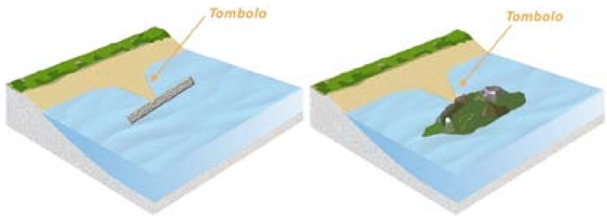
ABSTRACT: The process of global sea level rise is causing several significant changes in the coastal zone. Sea level rise and the frequency, strength and duration of storms are also occurring on the Polish coast. As a result, coastal protection measures, such as man-made engineering structure, are necessary. These engineering structures affect (among others) the marine ecosystem in different ways. Although the presence of such engineering structures can cause changes in the bathymetry of waterbody and the transport of sediments along the basin, it also slows down the erosion of the shoreline. For this reason, comprehensive knowledge of natural conditions, including dynamic and variable factors, is essential in the construction of a hydro-engineering structures. The correct determination of the environmental conditions helps to minimize environmental damage. Prior to interventions on the coast, the issues addressed in the paper should be analysed and studied. In this paper, the influence of shoreline structures on the main factors responsible for the development of tombolo phenomenon is discussed. In addition, the lithological diversity of surface sediments on which the rate of coastal erosion depends, is also discussed. An important element of the work is the descriptions of tombolo in Poland. They contain information on the causes of the phenomenon, as well as about the negative consequences of a disturbance of the hydrodynamic dynamics caused by the structure.

1 INTRODUCTION

Tombolo is a term used to describe a geomorphological feature [6, 46], a narrow strip (a sandy spit) connecting the mainland to the coastal island or two islands, consisting of a sand and gravel deposited by the ocean currents [61] (Fig. 1a) (Fig. 1b). Waves strike a beach obliquely are creating longshore currents that move sediment along the coast in a direction determined by the prevailing wave approach [63]. In most tombolo around the world, the sediment material comes from coastal erosion, rivers, underwater reefs and coastal glacial deposits [18]. Initially, so-called salients are formed. This flattening of the coastal zone is created in response to the erection of a hydrotechnical structure or barrier parallel to the shoreline [39]. If the hydrodynamic conditions do not change due to the long-term impact of the structure, a tombolo is formed. The tombolo phenomenon is a process involving the interaction between an obstacle and hydrodynamic forces, debris and the bottom's bathymetric profile. These factors after the movement of water, which in turn, affects the transport of the debris, a change in the bottom morphology, and the intensity of transport of the bottom sediment. This is particularly visible when the coastline is shifting towards a detached obstacle [11].

This phenomenon may have a natural or anthropogenic origin [5]. Natural tombolo occur when an obstacle is created by exogenous processes. Anthropogenic tombolo occur when the obstacle has a form of man-made infrastructure. An improperly constructed engineering structure may lead to local abrasions, bottom deepening, the occurrence of strong rip currents, and even deterioration of water purity in the future. For this reason, it is very important to determine the appropriate parameters for the construction of a breakwater or other hydrotechnical structures.



a) b)
Figure 1. Example of tombolo occurrence when the obstacle is a breakwater (a) or an island (b)

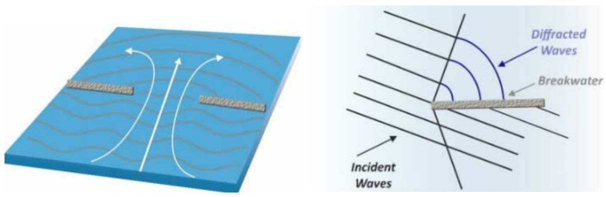
Figure 2. Satellite photo provided by Google Earth Pro showing the development of tombolo in Sea Palling, UK. Sources and dates of the images: Google Erath, 28.09.2020

The considerable complexity of the hydrodynamic processes occurring during tombolo formation leads to general regularities regarding the influence of waves and currents on sediment movement. Computer modelling (currently the most effective tool for complex analyses) are used to determine changes in the sea and the coastal zone. Considering the threat posed by the impact of a hydrotechnical structure on the coastline, various studies, including bathymetric analyses [37, 58], are being conducted on the tombolo phenomenon. Bathymetry change modelling provides information on the predicted change of a beach profile [68]. The tombolo phenomenon is analysed from both geological [53] and geomorphological aspects and hydrodynamics [2, 45]. The Simulating WAves Nearshore-SWAN model was used to determine the influences of waves on the tombolo phenomenon [4]. However, scientists at South Korea designed a CST3D model, which recreated the process of tombolo formation in this region. The model confirmed the hypothesis that the length of the hydrotechnical structure have an important role in the tombolo formation [25, 40]. In 1994, an algorithm was developed in a numerical coastline model that could calculate changes in the coastline position near the breakwater [62]. Since 2018, bathymetric measurements of this phenomenon carried out in Sopot, completed by research using satellite photogrammetry [60], UAV photogrammetry [59] and TLS laser scanning [57].

This review paper presents elements of the marine ecosystem that have changed due to the impact of the engineering structures known as tombolo forms. The paper is divided into eight sections. Section 1 introduces the tombolo phenomenon and reviews studies dealing with it. Sections 2 to 5 describe the factors related to the presence of a breakwater that influences the formation of a tombolo. The paper ends with general conclusions on dynamic processes forming a tombolo, while sections 6 to 8 discuss two examples of tombolos in Poland. The paper ends with general conclusions on dynamic processes forming a tombolo.

2 WAVE

Winds are the main energy-generated factor in the coastal zone, causing the development of wind waves [70]. The southern coast of the Baltic Sea is dominated by wind sea and swell [38]. The process that cause wind waves depend on the character of energy exchange between the sea and the atmosphere [12]. The wind sea move and grow as long as the wind blows and die out when the winds stops. The long-term influence of wind from one direction forms a swell [41], which is a hazard to navigation. A swell is characterized by short, discontinuous crest lengths that are closely spaced. Such a wind wave can reach a considerable height and have an irregular shape [27]. The strongest waving occurs in areas of shallow water depth (littoral zone). The largest waves (7-8 m) in the southern Baltic Sea can be observed in the autumn-winter period and are caused by long-lasting storms [71]. In the coastal zone, obstacles in the form of reefs, breakwaters, islands and rocks are quite common and disturb the propagation of waves. Waves commonly approach the beach obliquely–rarely at right angles to the beach. However, when waves approaching the breakwater change their characteristics due to the influence of this structure and participate in the formation of the coastline. One of the effects of engineering structures on the wind waves is diffraction [47]. Wave diffraction is a process in which the energy of waves propagates perpendicularly to the dominant direction of wave propagation. Fig. 3 shows the direction of the wave propagation with a wave diffraction scheme near a vertical wall.



a) b)
Figure 3. Figure showing the direction of the wave propagation at the ends of an obstacle (a) and the diffraction scheme near the vertical wall (own work based on: [50])(b)

Wave diffraction is considered as the bending of waves around an object. It is a kind of movement that allows waves to move at barriers into harbors as energy moves laterally along the crest of the wave [64]. The other water movement is a reflection. This is a phenomenon of bending of waves when they approach the shore. It causes the crest to rotate into a position parallel the depth contour of the bottom in the shallow water near shore. During refraction, most of the energy transported by the waves is dissipated and the remaining energy is used to generate currents that cause sediment transport, both along and across the shore [36].

There are three types of wave refraction near the shore (Fig. 4):

– Spilling with the height of the wave decreasing gradually and foam-forming crest of the wave
– Plunging when part of the wave crest is rolled and breaks after reaching the maximum wave height
– Surging when after refraction the wave creates a surf stream that reaches the shore

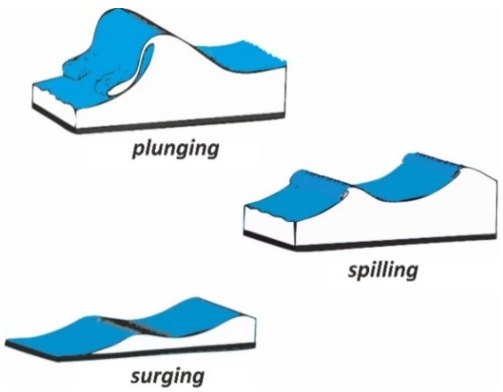


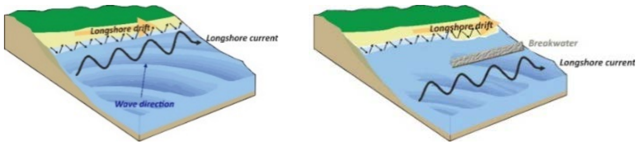
Figure 4. The figure shows types of wave refraction (own work based on [36])

The above-mentioned refractive-diffraction processes form a so-called shadow zone, which influences the transport and morphology of sediments [29].

3 CURRENTS

In sea basins, currents are an essential element responsible for water movement. The ocean current is defined as the progressive movement of waters, characterised by a distinctive direction of the resultant movement and velocity speed equal to the average velocity of elementary masses [12]. Currents can be formed under the influence of wind, pressure gradient, differences in temperature, salinity and gravity [8]. In the short-term perspective, surface currents [15] in the Baltic Sea are generated by wind and their distribution in the coastal zone depends on bottom topography [17], and coastal morphology. Moreover, in the Baltic Sea, there is a local deep ocean current, resulting from differences in depth associated with salinity and temperature. In addition to local currents, large-scale circulation is also observed in the individual Baltic Sea basins, which takes the form of cyclonic vortices [48], resulting from the interaction of the Earth's rotation and changes in water depth.

In the area between the breakwater and the shore, coastal currents play a special role. Characteristic current circulation is occurs when wave propagation direction is diagonal to the shore, generating a parallel and perpendicular flow of water [56]. A longshore current which occurs when the wave approaches the shore at a certain angle (Fig. 5.a) is the strongest in the littoral zone. Longshore currents are caused by refractive waves, e.g. by the influence of hydrotechnical structures.

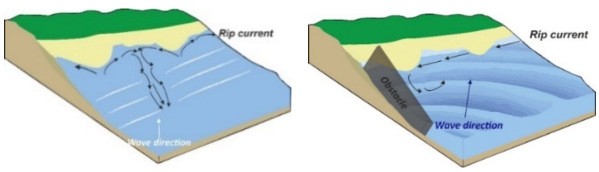


a) b)

Figure 5. Figure showing the longshore current in the shore zone, without the influence of the structure (a) (own work based on: [56] and longshore current with the influence of the engineering structure (breakwater) (b)

The main factor contributing to the formation of longshore current is the so-called radiation stress [31]. The term radiation stress is defined as the excess of the momentum stream in a sea area, which results from the wave motion [48]. The currents generated in this way flow parallel to the shore. The existence of technical infrastructure in the coastal zone causes weakening of the longshore current which, in consequence, leads to excessive accumulation of sediments along the coastline. This is visible in a coastal zone developed with structures (groins, piers, breakwaters) where a shore bulge is created (Fig. 5b).

Another important current responsible for transporting thicker sediment fractions from the coastal zone into deeper sea areas and creating peculiar sedimentary structures is the rip current [28]. Rip currents are usually generated by waves hitting the shore perpendicularly and are the effect of the convergence of water masses in the hitting zone as a result of the so-called process of water pumping by the breaking waves [52]. The figure below exemplifies how rip currents (Fig. 6.a) are created near a breakwater (Fig. 6.b).



a) b)

Figure 6. Figure showing an example of rip currents (a) and an example of the formation of rip current near the breakwater together with the direction of the wave (b) (own work based on: [48])

In addition to affecting the movement of sediments in the coastal zone and the formation of coastal landforms. These currents contribute to many drownings [55], especially near breakwaters and other man-made coastal structures. This is due the fact that the water masses refracting the obstacles and changing their direction towards the sea. This creates a so-called corridor where rip currents can reach speeds of up to about 0.2-0.5 m/s during storms in the South Baltic [16]. A particularly high risk for a change in direction of the wave exists where the water meets the shore at a certain angle due to obstacles or flows parallel to the shore. In addition, the occurrence of rip currents leads to stagnation and deterioration of water cleanliness, which is conducive to the development of cyanobacteria in summer [14].

4 COASTAL ZONE STRUCTURE

The sedimentary material [10], which is largely involved in the formation of new relief in the coastal zone, comes mainly from the lithological structure of subsoil, the geomorphological processes taking place and, to a small extent, from leaching of Pleistocene sediments in the seabed and transport of material by the rivers [10]. The deposition of individual sediments on the seabed occurred under the influence of the great Atlantic transgression, which initiated the processes of abrasion, redeposition and deposition [42]. The destruction of cliffs in the process of abrasion brings Pleistocene clay and sand sediments to the sea [20]. Rivers, in turn, are a source of fluvial sediments, which include: sands and gravels that were previously eroded. Another factor in the supply of material to the coastal zone is eolith. Material carried by the wind from the land to the sea. Typically, the beaches are enriched with sediment from beach nourishment supplied to the shore and from deeper sea areas. Fig. 7 shows the sources of sediment in the coastal zone in the southern part of the Baltic Sea.

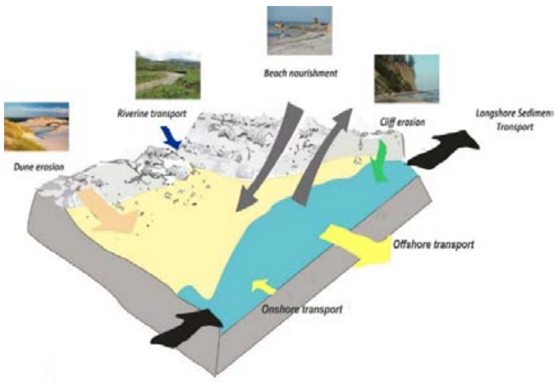


Figure 7. Figure showing the sources of sediment in the Baltic Sea

Due to the need to distinguish sediment types in the Baltic Sea region, Shepard's sediment classification and Wentworth's grain size classification were used [42]. The lithological differentiation of the surface sediment is characteristic for the geological structure of the ice sheet and results from material selection during transport under the influence of wave and bottom currents [26]. In the littoral area, the southern Baltic Sea is dominated by fine-grained sands [67]. Quartz predominates in the sands, and lamina are found, often enriched in heavy minerals and shells with abrasion marks. Other, coarser, sediment types occur locally, especially near the cliffs. Outside the coastal zone, there are medium-and coarse-grained sands, as well as sands of varying grain, sandy gravels, gravelly sands and gravels. The sediment distribution is indicative of the highly dynamic nature of processes occurring in the seabed [43]. In the area of the tombolo formation in Sopot and Kołobrzeg (Fig. 8), there are three granulometric types of sediments: fine-grained, coarse-grained, and medium-grained sands. However, near the coastline fine-grained sand predominates. Medium and fine-grained sands in the coastal zone are the group of sediments that are most easily moved because sediments in the coastal zone are affected by storm waves that impact the seabed and cause in the erosion of sandy sediments. Nevertheless, beaches with fine-grained sand are frequently found in areas with little influence from waves or tidal currents.

a) b)

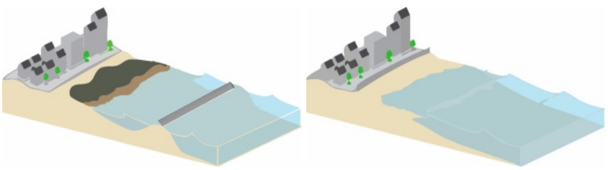
Figure 8. Map showing the lithological diversity of surface sediments on the area adjacent to the pier in Sopot (a) and Kołobrzeg (b) according to the classification of F.P. Shepard (own work based on layers available from: [32])

Unfortunately, the natural distribution of sediments is increasingly disturbed by anthropogenic factors [51]. The construction of breakwaters, hydrotechnical development of the shore and dredging lead to local changes in hydrodynamic conditions and associated lithodynamic processes. Hydrotechnical structures lead to the accumulation of sandy sediments in the shoreline zone, while dredging leads to a deterioration of the living conditions for benthos [22]. The change in the direction in which waves approach the leeward side of the breakwater is responsible for sediment accumulation. Groynes are another example as they restrict the flow of water along the shore, resulting in accumulation of material on the beach [22]. The beach cannot rebuild after a storm surge due to disruption of circulation along the shore. Most engineering structure cause the formation of new geomorphological forms and interrupt of the natural sediment circulation.

5 SEDIMENT TRANSPORT

Sediment transport is one of the most important lithodynamic processes, because it determines the formation of shoreline forms and the formation of erosion and accumulation zones near hydrotechnical structures. In the coastal zone, sediments are transported within the depth range with a noticeable effect of surface waves on the seabed [35]. Sediment transport begins with sluggish movement, accumulation of individual grains in the bottom zone, or in close proximity. As the waves gradually become more powerful (for example, during storms), the wave motion becomes more intense and more grains are detached from the bottom. This begins the process of moving the sedimentary material. The magnitude of transport is rather random depending on factors such as the diameter of the sediment grains, their weight (taking into account the buoyancy force), roughly defined structural features, the roughness of the bottom and the viscosity at the water-sediment interface. Two directions of sediment transport can be distinguished: longshore [3] and cross-shore (onshore/offshore). The main factors determining the intensity of longshore and cross-shore sediment transport are the wave parameters at the external boundary of the coastal zone, themorphology of the coastal platform and the sediment composition [1].

Longshore transport consists of the accumulated parallel movement of beach and coastal sand towards the shore [54]. It is caused by waves approaching the shore obliquely causing movement of materials along the beach by a process called drifting. This is formed by tides, wind, and wave action, and creates a peculiar system of ocean currents along the coast. The strongest is the longshore current [1]. Longshore movement of sediments is particularly noticeable in the shore zone, which has been developed with structures perpendicular to the shore. Strong downstream erosion or upstream accumulation in the shoreline area is then clearly visible [48]. A negative sediment balance develops behind the obstacle and a positive sediment balance appears in front of it, which may contribute to the formation of new geomorphological reliefs (Fig. 9.b). As breakwater blocks sediment runoff, it causes losses in the adjacent areas that were previously supplied by it [51]. When there are no obstructions, the sediment material is transported along the shore and deposited in more distant sections on the shore or beach (Fig. 9.a). The sediment participates in the natural exchange of sedimentation, which demonstrates itself in processes that lead to leveling to the coast or erosion of the part of land extending towards the sea [24].



a) b)
Figure 9. Drawing presenting the beaches with natural sedimentation exchange (a) with the influence of a breakwater (b)

Cross-shore sediment transport consists of the movement of sediment perpendicular to the shore under the influence of waves and balancing wave currents. It includes both transport towards the sea during storms and transport towards land, which predominant during calmer periods [1]. Sediment transport in the transverse direction is associated with local changes of the seabed aimed at rebalancing [44]. It is important to observe transport to predict the seasonal shoreline variability and pollution. Excessive sedimentation contributes to the increase in pollution by accumulating harmful substances that can a negative impact on both the marine ecosystem and humans [30]. This is why it is so important for cities to intervene and clean beaches when soil material is deposited near the beach.

6 TOMBOLO IN KOŁOBRZEG

The Polish coast is largely sandy and vulnerable to climate change threats [22]. Previous observations and analyses show a rise in sea level [69, 71], an increasing frequency of extreme meteorological phenomena and storms, which leading to an increasing area affected by coastal erosion. This is particularly noticeable east of Kołobrzeg and affects up to 334 km of the Polish coastline (according to the coastline of Maritime Office) [33]. The sea level fluctuation in this area reaches 3.4 m and the sea is retreating at an estimated rate of 0.9 m/year [24]. Taking into account the changes in coastal morphology, several coastal protection measures have been implemented in Kołobrzeg.

Beach nourishment measures have been regularly carried out in this region, every two to three years since 1993 [22]. Unfortunately, the reclaimed beach is destroyed not only by storms, but also by erosion of the coastal bottom, where continuous deepening is observed. Investments in the construction of maritime infrastructure play a significant role in here. In 2010, as part of the Coastal Protection program (2003) [13], the old breakwater was demolished and a new 450m-long rubble-mound western breakwater was constructed and the eastern breakwater was extended by 150m [19]. In 2012, a 3-km-long tailrace was constructed and 35 groynes were installed [22]. However, due to the large bottom depth in this area and the negative debris balance, increased wash-off of beach sediments occurs during major storm surges. Despite the presence of factors threatening beach reclamation, the formation of tombolo can be observed on the beach in Kołobrzeg after a storm, which contributes to the accumulation of pollutants, algae and bacteria (Fig. 10a) (Fig. 10b).

a) b)
Figure 10. Kołobrzeg beach-view of the eastern breakwater (a) and groins (b)

Unlike many other tombolos, these occur mainly seasonally. In Kołobrzeg, the extent of this phenomenon in every year, which is due to meteorological factors affecting the hydrodynamics of the area. It is most noticeable when an anticyclone forms over the Polish coast, which is characterised by calm atmospheric conditions. The measures taken to protect and reclaim the beach and coast did not meet the initial expectations, and even worsened the condition of the beach. Groynes and an extended breakwater stop the flow of water along the coast, causing fine sand and silt to settle on the beach. In addition, the protective structures hinder the natural reclamation of the beach during major water surges [23]. In the future, tombolo formation in Kołobrzeg may prevent bathing due to the formation of a muddy sea bottom near the beach and the occurrence of rip currents. However, there is no doubt that it was necessary to build a hydrotechnical structure to mitigate the effects of coastal erosion.

7 TOMBOLO IN SOPOT

Thanks to the number and complexity of the measurements [58], the tombolo in Sopot remains the best studied phenomenon of this kind. It is located on the breakwater in the town of Sopot, in the southern part of the Baltic Sea, on the Gulf of Gdańsk. The Gulf of Gdansk is a special area because there is a very peculiar long peninsula in the vicinity, which strongly influences propagation and thus the energy of the waves [9]. In this region, storm surges have an uneven distribution throughout the year, with a maximum number of surges between September and February. The strongest surface wind ripples is generated from north to east, causing extreme waves. However, it must be taken into account that wind undulation in the coastal zone, is subject to significant changes associated with decreasing depth and increasing bottom friction, which may additionally contribute to increased movements of bottom sediments along the coast [7]. On 13-14 October 2009, a severe storm took place along the eastern part of the Polish coast, destroying many hydrotechnical facilities and structures, including the breakwater in Sopot [34]. This was the argument for the construction of a marina to protect the coast and development the maritime infrastructure in the area. The orgin of the tombolo phenomenon dates back to 2011 when the marina became operational. The analysis of the coastline [60] clearly confirms the positional changes due to the influence of the hydrotechnical structure built in 2011. The structure, which is an extension to the pier, started to cause changes in the coastline in the form of emerging tombolo. Bathymetric measurements carried out by the Maritime Office in Gdynia since 2010 both the needs of the construction of the facility and due to changes in the coastline. In addition, a survey and hydrographic team has been conducting bathymetric measurements since 2018 unmanned surveying vessel (USV) [59] photogrammetric measurements from unmanned aerial vehicles (UAV) [5], terrestrial laser scanning (TLS) [57] and precision receivers of global navigation satellite systems (GNSS). Based on analysis and research, it was determined that the developing tombolo phenomenon constitutes a threat to tourism in Sopot, and failure to intervene in the future may lead to significant changes in the beach structure. Increased blooms of cyanobacteria and algae, especially green algae [65] are increasingly observed in the resort, mostly on the south-western side of the marina. Blooming causes water turbidity and reduces water transparency. Eutrophication of the sea is one of the major threats to the correct functioning of the marine ecosystem. In addition, mud is deposited on the boundary between the coast and the beach, where it lingers in the summer and creates a peculiar smell.

Another visible effect is that the water near the marina is getting shallower. Failure to update hydrographic maps in the eastern part of the pier and the southern part of the marina on an ongoing basis may cause damage to vessels mooring in the marina. The negative consequences of the erected structure also include the occurrence of rip currents, which are responsible in many cases for drowning [21]. In terms of the dynamics of changes in the morphological parameters of the waterfront, the shore section between the cliff in Gdynia Orłowo and the pier in Sopot is very distinctive because it is supposed that material from the cliff is deposited at the pier in Sopot. Due to the uneven distribution of sediments, the Maritime Office in Gdynia undertook to reclaim the beach in Gdynia using sand obtained from the vicinity of the Sopot pier. In 2020, 58 thousand cubic meters of sand from the Sopot pier area was used to reclaim the seashore [66].

a) b)

Figure 11. Beach in Sopot Orthophotomap (a) [5] and a photo showing blooming algae (b) of the area adjacent to the pier in Sopot [65]

As a result of the development of the marina, a process was set in motion, the effects of which are felt mainly in tourism. Sopot is a resort town that can be severely affected by an ecological disaster if the appropriate response is not taken. Although the Sopot authorities occasionally extract black sand and dredge the bottom, this is not a solution to the tombolo problem.

8 CONCLUSIONS

Tombolo is a complex oceanographic phenomenon that is strongly conditioned by the interactions between an obstacle and hydrodynamic forces, debris and the bathymetric profile. In this paper the components that contribute to the formation of this phenomenon are discussed. These components are presented along with their impact on hydrotechnical structures [49]. In addition, the lithological diversity of surface sediments is described, on which the rate of sediment exchange depends. The influence of these factors was discussed with reference to the hydrometeorological conditions prevailing in the south Baltic Sea using the two tombolo examples mentioned in this article. The two examples are among the most common phenomena of this type in Poland, but they differ in their dynamics and frequency. The tombolo in Sopot has been the subject of research and analysis for many years. It is also worth emphasising the need to take environmental changes into account before planning construction, since any intervention in the environment causes a disturbance in the naturally occurring processes. For this reason, using the examples given, this paper uses examples to highlight the negative effects of such phenomena as: algal blooms, cyanobacteria, rip currents, changes in bathymetry, shoreline displacement and changes in the structure of the coastal zone. These phenomena should be a subject of more comprehensive studies in the future to better understand the tombolo phenomenon and reduce the factors that contribute to its formation. A complete analysis of these factors will help to reduce the effects and better understand the impact of the different components of this oceanographic phenomenon.

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